Fertilizer requirements in 2015 and 2030

Food and Agriculture Organization of the United Nations

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Foreword

In May 1997, at its meeting in Beijing, IFA's Fertilizer Demand Group, of which I am the convenor, recommended that longer-term projections of fertilizer demand should be prepared, based on expected developments in agricultural production. Following discussion with relevant experts in the Food and Agriculture Organization (FAO) of the United Nations in March 1998, it was recommended that a working group from TFI (The Fertilizer Institute) of the United States, the Land and Water Development Division of FAO and the US Department of Agriculture's (USDA) Economic Research Service should be established to study this question.

At the time, FAO was preparing forecasts of world-wide crop yields and areas for their new study in the "World Agriculture Towards .... " series. This is the fourth study since 1979 and this time it forecasts agricultural production to the years 2015 to 2030. The crop production forecasts resulting from previous studies have proved to be remarkably accurate. Projected rates of fertilizer consumption were derived from these agricultural production forecasts and the fertilizer application rates given in the publication by FAO/IFA/IFDC (International Fertilizer Development Centre) entitled "Fertilizer Use by Crops".

The results indicate that annual fertilizer use must increase from the 134 million tonnes average between 1995 and 1997 to about 180 million tons by 2030, with a range of plus or minus 10% depending on the improvement in the efficiency of fertilizer use, in order to attain the yields projected in FAO's study. This represents an annual growth rate of about 1 percent per annum, or 1.5 million tonnes total nutrient per year over 34 years. This compares with an average annual increase of 3.3 percent, or 2.9 million tonnes nutrient per year during the 34 years between 1961 and 1997. The lower rate of increase in fertilizer use reflects a slowdown in crop production growth shown by the FAO study, and low growth of fertilizer use in the industrialized regions of the world, which are near optimum levels of fertilization. Some growth is expected in

Central and East Europe but this represents a partial recovery from the slump which occurred in the early 1990s, and fertilizer consumption in these regions will still be below the 1990 level. Most of the increase in world fertilizer consumption will be in Asia and the Americas. It seems likely that fertilizer use will remain low in sub-Saharan Africa.

This joint study represents an unprecedented coordinated effort, involving five organizations, in order to arrive at a result which is of fundamental importance for world agriculture and for the mineral fertilizer industry. It is an excellent example of fruitful cooperation between the private sector and the public sector.

Glen Buckley
IFA Fertilizer Demand Group

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Acknowledgement

This paper is based on the work of S. Daberkow (USDA), J. Poulisse (FAO) and H. Vroomen (TFI).

Economists and agronomists are locked in debate about likely future yields. Since the method of the economists is to predict future outcomes from past performance, economists expect success to continue. And since for the scientists future success depends on discoveries they will have to make and do not now know how to make, the scientists are doubtful. At its core, this is a disagreement about the pace of technical change. (Robert Socolow, 1998)

Long-term projections of international agricultural production and/or resource requirements are fraught with assumptions, data limitations, and ill-understood economic and physical relationships (e.g. note Socolow above). Despite these well-known deficiencies, there continues to be considerable interest in future agricultural production from a number of quarters. Public agencies charged with developing and implementing food, agriculture, environmental and trade policies; organizations concerned with food security issues, and agri-businesses focused on the production, processing and marketing of agricultural commodities and inputs are constantly assessing the future state of the global agricultural sector. Investment planning and public policy initiatives are often better served when a systematic approach is employed to quantify and explicitly examine the relevant factors affecting the future state of agricultural production and resource requirements.

There appears to be some consensus in the research community about the likely future path of global agricultural production and resource use (IFPRI, 1995; NAS, 1998). Aspects of this consensus can be succinctly summarized as follows: growing world population and per caput incomes will likely require more intensive agricultural crop production. Higher yields will, in turn, increase

the demand for agricultural inputs. Furthermore, future agricultural cropping patterns will reflect shifts in diets (e.g. greater meat consumption). Greater opportunities for agricultural trade may also lead to regional shifts in world crop production. At the same time there will likely be economic and environmental incentives to improve the efficiency of fertilizer use over current levels in all countries, but especially in the developed countries. The overall goal of this paper is to examine the cumulative effect that these forces may have on future fertilizer use.

OBJECTIVE

The specific objective of this paper is to explore the bounds on the amount of fertilizer needed to support FAO projections of agricultural commodity production for 2015 and 2030. Three alternative assumptions are made to relate yield or production projections and available data on fertilizer application rates to estimate total fertilizer or nitrogen fertilizer use in 2015 and 2030. The assumptions are:

- a base case where total fertilizer use grows at the same rate as crop production until to 2015 and 2030;
- a fertilizer growth case where total fertilizer use efficiency is expected to improve for all crops and countries; and
- a case where nitrogen fertilizer use in the future is based on the early 1990s' relationship between yields and nitrogen application rates for the major cereal crops (wheat, rice and maize) in the major producing countries. Wheat, rice and maize were chosen for more detailed analysis because they account for over half of the nitrogen fertilizer consumed on a global basis and nitrogen can have adverse effects on the environment.

This paper exploits two relatively new sources of data to project the use of mineral fertilizers by major crop and region in 2015 and 2030. FAO has recently constructed a preliminary estimate of 2015 and 2030 yields and areas for the major crops by country. These estimates rely on country forecasts of essential variables affecting the demand and supply of agricultural commodities. FAO, the International Fertilizer Development Centre (IFDC) and the International

Fertilizer Industry Association (IFA) have recently updated their joint estimates of fertilizer application rates by crop and country.

The paper begins by briefly reviewing recent efforts by others to identify and quantify the essential factors influencing the growth in demand and supply for agricultural commodities, since fertilizer use is typically characterized as derived from the demand for agricultural commodities. Several studies that estimate long-term fertilizer use are also reviewed, followed by a more thorough discussion of the forecasting methods and data. Finally, the results, caveats, and implication sections conclude the paper.

Cereal Demand and Supply

The traditional economic modeling approach to explaining and/or projecting country or global food consumption focuses on the factors which influence aggregate demand and supply (e.g. see IFPRI, 1995). The most important demand determinants are population, income, commodity prices, and dietary tastes and preferences. Growth in demand is governed largely by the rates of growth in population and income although commodity prices and changes in diet can be influential[1]. For example, growing income levels often lead to greater demand for meat products and hence increased demand for feed crops[2]. Crop supply is assumed to be mainly a function of cropland and yields, but crop prices and agricultural policies can also play a role in accelerating or retarding changes in planted acreage. For most countries, the potential for cropland expansion is limited. Thus, increases in future crop production will result primarily from higher yields. Converting rainfed cropland to irrigated land or multiple cropping can result in increased yields, as can the more intense use and management of agricultural inputs (fertilizers, pesticides, etc.). In the longer run, public and private investments in agricultural research may influence

[1] IFPRI (1995) estimates that 90 percent of the rate of increase in cereal demand will be due to population growth and the remainder primarily to income growth.

[2] The following discussion uses the terms rate of demand growth and growth rate of consumption interchangeably. Technically, the growth rate of demand equals the growth rate of consumption or use only if real prices remain constant (Johnson, 1998). In other words the growth rate of consumption is the result of the shift in the demand function and the change in real prices.

the growth in crop yields. At the country level of aggregation, any mismatch in production and consumption results in the potential for stock accumulation or export, or in a deficit that may lead to imports if income permits. For countries without adequate income, malnutrition or food aid is the common outcome.

Demand Outlook

Given this framework, what are the recent trends and outlook for cereal demand and supply?[3] At the world level the most notable trend is the steady decline in the annual population growth rate from 1.8 percent for 1980-1991 to 1.5 percent projected for the period 1991-2010, with further declines expected into the middle of the next century (Table 1). The bulk of the decline will be in developing countries, which conceivably could reduce their food insecurity.

TABLE 1
Actual and projected annual growth rates for population and cereal consumption and production for selected years

Country categories	Years	Population	Cereal consumption	Cereal production
Developed countries	1970-1980[1]	0.8	1.6	2.4
	1980-1990[1]	0.7	0.7	0.6
	1991-2010[1]	0.6	0.7	1.1
	1993-2020[2]	n.a	0.5	0.9
Developing countries	1970-1980[1]	2.0	3.6	3.1
	1980-1991[1]	2.1	2.8	2.7
	1991-2010[1]	1.8	2.1	1.9
	1993-2020[2]	na	0.5	0.9
World	1970-1980[1]	1.7	2.5	2.7
	1980-1991[1]	1.8	1.8	1.6
	1991-2010[1]	1.5	1.6	1.6
	1993-2020[2]	na	1.3	1.3
	2020[3]	1.0	na	na
	2050[3]	0.4	na	na

[1] IFPRI, 1995, page 28: population estimates; pages 86-87: 1991-2010 estimate is average of three projections; [2] Rosegrant, Leach and Gerpacio, 1998: calculated from Table 20 baseline. [3] Alexandratos, 1998b. na = not available.

[3] According to Dyson (1998; page 1) cereals have a central place in the human diet. "Today roughly half of the world's cropland is devoted to growing cereals. And if we combine their direct intake (e.g. as cooked rice or bread) with their indirect consumption – in the form of foods like meat and milk (about 40 percent of all grain is currently fed to livestock), then cereals account for approximately two-thirds of all human calorie intake."

With declining population growth, aggregate growth in demand for cereals is likely to slow significantly. On a global scale, cereal production when compared with cereal use: (i) grew faster during the 1970s as world stocks increased; (ii) grew slightly slower during the 1980s as world stocks declined; and (iii) is expected to grow at the same rate in the future. One consequence of these growth patterns was the almost continual decline (nearly 40 percent) in real crop prices between 1960 and 1990 (Johnson, 1998). To the extent that demand stimulates supply, the slowing rates of demand growth are expected to weigh down output growth (Dyson, 1998; Alexandratos, 1998a; Johnson[4], 1998). Conversely, higher real prices could clearly stimulate additional production.

With respect to cereal production and consumption, the situation and outlook is quite different between the developed and developing countries (Table 1). The rate of growth in production and consumption in developing countries is, or is expected to be, higher in all time periods compared to developed countries, partly reflecting the lower production and consumption base levels in developing countries. High birth rates, growing incomes, and in the case of production, the adoption of more intensive agricultural practices, also help explain the larger growth rates for developing countries. During the 1970s, developed countries increased production faster than use, which was the opposite of the developing countries[5]. Growth in production and consumption was more evenly matched in the 1980s in both groups of countries. Future projections are for the growth patterns of the 1970s to reappear with the implication that cereal trade will be much more important in the next millennium. The excess productive capacity of North America, Western Europe, the Former Soviet Union, and Oceania will supply the growing markets of the Middle East, Asia, and Latin America (Dyson, 1998). According to this scenario, Sub-Saharan Africa remains an importer via its acceptance of food aid. A more recent forecast (Rosegrant *et al.*, 1998) reports similar results to the IFPRI study but finds that cereal production and consumption growth may be even lower (1.3 percent annually) in the first part of the next century.

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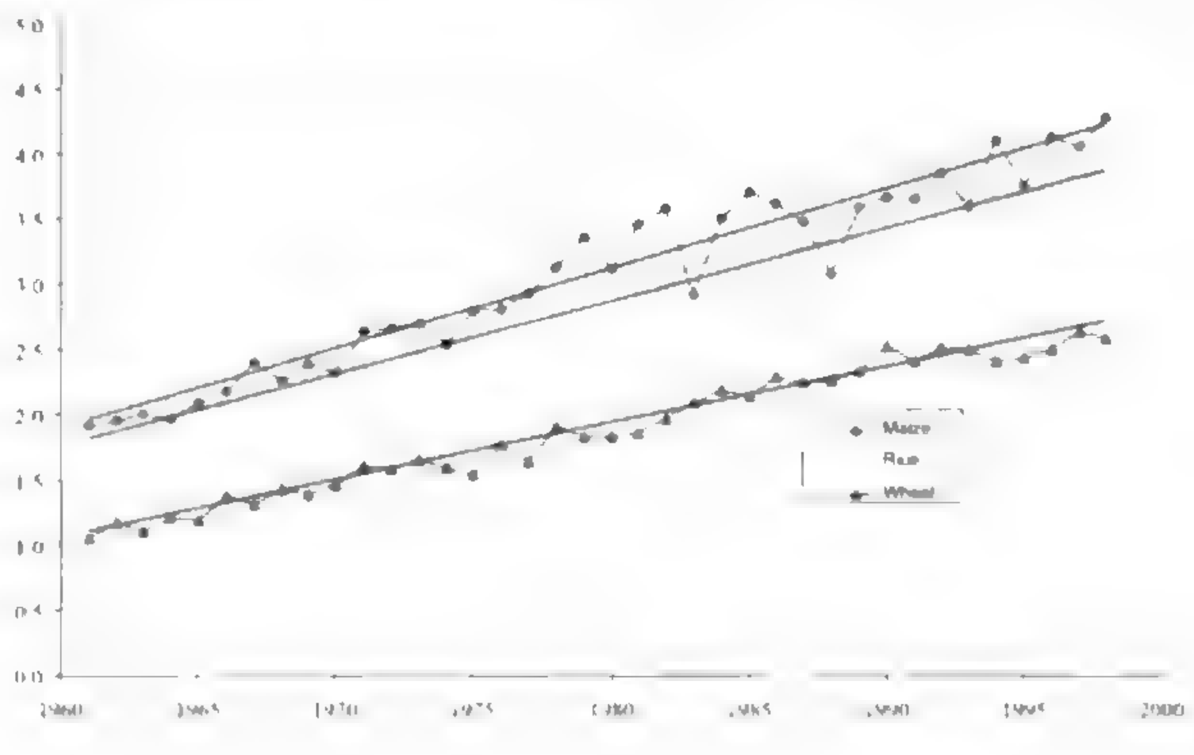
4 Johnson (1998) suggests that the real long-term threat to food security is the prospect of continued low international commodity prices leading to reduced governmental support for agricultural research.

5 Rosegrant *et al.* (1998) note that rising income along with urbanization in developing countries will encourage more meat consumption, which will induce strong growth in maize production – a major fertilizer consuming crop.

SUPPLY OUTLOOK

While population growth tends to drive increases in demand for agricultural commodities, growth in supply is typically attributed to yield and cropland area changes[6]. Although the potential for increases in arable cropland is limited for most countries, more intensive cultivation through irrigation and multiple cropping can enhance output. But the increase of irrigated area is slowing. The global rate of growth of irrigated area has declined from over 2 percent annually during the 1960-80 period to around 1 percent during the 1980s (Oram and Hojjati, 1995). Increases in arable and permanent cropland have slowed from about 0.3 percent annually between 1960 and 1980, to less than 0.2 percent in the 1980s. Yield increases will likely remain the engine for output growth (Dyson, 1998). For example, the global trend in cereal yields has not shown a deviation from its long-term, nearly linear positive slope (Figure 1)[7]. Most studies assume that improved genetic stock, better cultural practices, enhanced

FIGURE 1
Trends of world cereal yields 1961-98, t/ha (Source: FAO)



[6] Bruinsma (1998) estimated that about 80 percent of the increase in crop production between 1990 and 2010 would come from more intensive land use and increased yields and multiple cropping.

[7] Note that a linear growth curve will result in declining yield growth rates as the base level rises over time.

pest control and host resistance, and refined nutrient management will contribute to further yield growth[8]. Another contributing factor to future yield increases is the level of public and private agricultural research investments, which are typically assumed to remain constant in inflation-adjusted currency (Agcaoili and Rosegrant, 1995).

Fertilizer Demand

Fertilizer use is typically characterized as derived from the demand for agricultural commodities. Slowing growth in food demand does not mean that aggregate demand for fertilizer will decline. On the contrary, growing population and income will translate into greater food needs, which will come from a nearly static land base. A more intensive agriculture, as reflected in ever-increasing yields, means more use as well as more intensive management of agricultural inputs.

The role of mineral fertilizer in support of growing demand for agricultural commodities is well-established (Oram and Hojjati, 1995). Over the last 30 years, there has been a positive correlation between cereal production and fertilizer use in developing countries, which currently use the bulk of mineral fertilizers and exhibit the largest rates of growth relative to developed countries (Figure 2). Until the early 1990s, developed countries (excluding Eastern Europe and the former Soviet Union) exhibited a similar correlation between cereal production and fertilizer use (Figure 3)[9]. Replenishing nutrient-depleted soils and maintaining or enhancing the current level of fertility in other soils are necessary to exploit the growth in potential yields. However, more efficient use of fertilizer, through improved timing, split applications, site-specific management, crop rotation, soil testing, etc. can facilitate higher yields with

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8 Rosegrant *et al.* (1998) have detected a modest slowing of the yield growth rates since the early 1980s. They attribute the decline to slowing demand growth and falling real commodity prices, which discourages the adoption of more intensive agriculture.

9 Cassman (1998) notes that three factors have been responsible for yield and production increases: (i) new cereal varieties; (ii) investments in irrigation infrastructure; and (iii) increased application of nitrogen fertilizer which allowed the production potential from irrigation and improved genetics to be realized.

FIGURE 2
Fertilizer consumption and cereal production in developing countries, million t (Source: FAO)

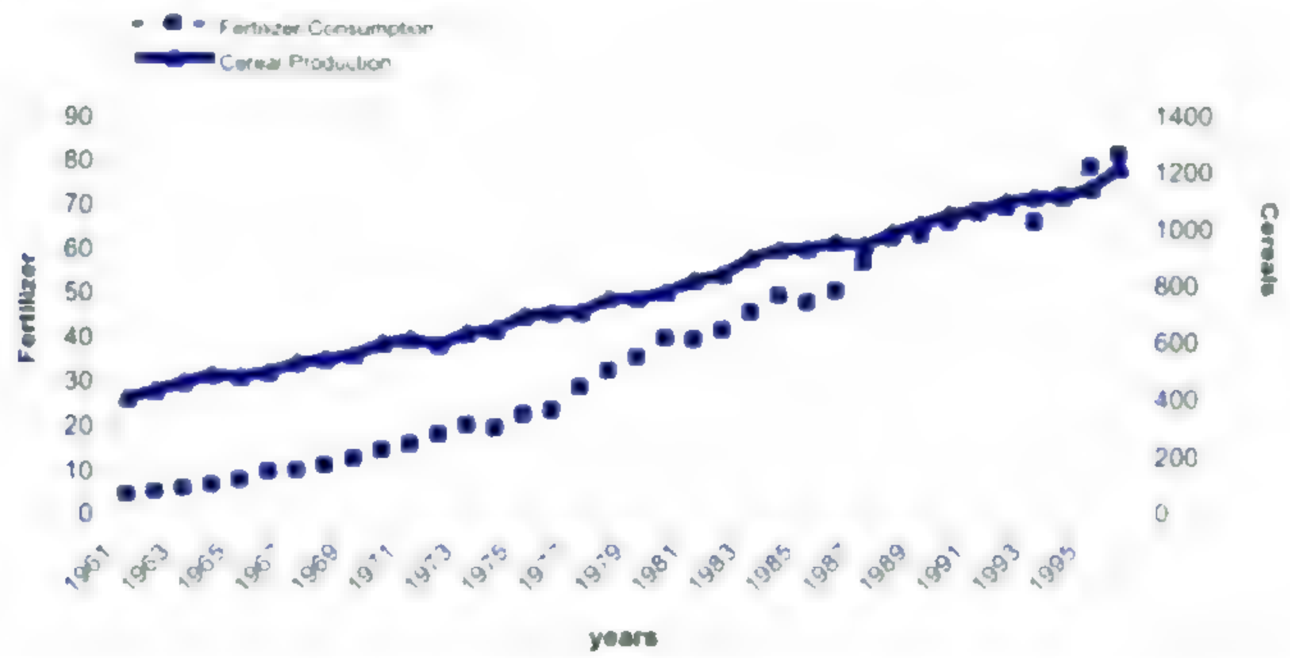


FIGURE 3
Fertilizer consumption and cereal production in developed countries, excluding Eastern Europe and FSU, million t (Source: FAO)

the same, or even less, fertilizer. Developed countries, especially those in North America and West Europe, appear to be exhibiting growing nutrient use efficiency, especially for nitrogen (Frink *et al.*, 1998).

Several recent studies have suggested that the expected continual yield (and production) increases during the next 30 years will likely require increases in the use of fertilizers. For example, based on an econometric model, Bumb and Baanante (1996) estimated that effective world demand for fertilizer would

TABLE 2
Fertilizer use and annual growth, 1959/60, 1989/90 and 2020

Country category	Fertilizer use (million t nutrients)			Annual growth (%)	
	1959/60	1989/90	2020	1960-90	1990-2020
Developed	24.7	81.3	86.4	4	0.2
Developing	2.7	62.3	121.6	10.5	2.2
World	27.4	143.6	208	5.5	1.2

Source: Bumb and Baanante, 1996

increase 1.2 percent annually between 1990 and 2020 (Table 2). This is much slower than the 5.5 percent annual growth during the 1960-90 period when fertilizer was becoming widespread in both developing and developed countries. The lower growth rates reflect "a higher base, limited potential for further growth, and changing policy environments. Because of the already high application rates, environmental concerns, reduction in farm support programs, and trade liberalization policies, fertilizer use in developed countries is projected to increase only modestly" (Bumb and Baanante, 1996: page 2). In absolute quantities, they expect total fertilizer use to increase from 143.6 to 208 million nutrient tons between 1990 and 2020 with developing countries surpassing use in developed countries during the mid-1990s. This scenario correlates closely with the food production outlook presented above: cereal production growth in developing countries will out-pace that of the developed countries during the first part of the next century.

Other less exhaustive studies have also ventured estimates of future fertilizer use. For example, Plucknett (1995), suggested that intensification of agriculture might require as much as a 7 percent increase per year in fertilizer use to meet future food needs. Alexandratos (1998a) forecasted annual fertilizer growth rates of 3.8 percent between 1989/90 and 2010. Dyson (1998) estimated that between now and 2025, global use of mineral nitrogen will double, which implies an annual compound rate of growth of 2.26 percent. Gilland (1998) asserts that the 74 million t/year of nitrogen fertilizer currently used for agricultural production will grow to 200 million t by 2050—a growth rate of 1.89 percent annually[10]. Finally, Frink *et al.* (1999), using a deterministic

[10] A legacy of these estimates of large future quantities of nitrogen use has been a growing concern about excessive fixed nitrogen in the environment (e.g. Socolow, 1998).

model based on the rate growth of population, gross domestic product and crop production, expect nitrogen use to grow by 1.1 percent annually from 1990 to 2070.

DATA

Crop production projections

As part of its effort to update the Agriculture Towards 2010 report, FAO is projecting yields and harvested area for 34 crop categories by country (Alexandratos, 1995a). FAO's estimate of 1995-97 actual production; preliminary projection of crop production (yield times area harvested) for 2015 and 2030. Expected annual growth rates for 1995-97 to 2015 and 2030 are presented in Table 3. The ten major fertilizer-consuming crops are highlighted. The production projections are based on FAO's estimates of country-level: (i) population and income levels and growth; (ii) future yield growth; (iii) cropland quality and quantity constraints; and (iv) assumptions about agricultural trade flows.

Several overall trends, and notable exceptions, can be gleaned from FAO's preliminary projections. Growth in the production of most crops is expected to

TABLE 3
Actual production of major crops and fertilizer use for 1995-97 base year and projected crop production of major crops in 2015 and 2030, million t
(Source: FAO)

	Production[1]			Average annual growth (%)		Fertilizer use	Nitrogen use
	1995-97	2015	2030	2015	2030	1995-97	1995-97
Wheat	509.6	689.8	805.4	1.5	1.3	24.7	16.3
Rice	534.5	690.4	755.5	1.3	1.0	21.3	15.0
Maize	516.2	720.8	872.9	1.7	1.5	19.3	12.1
Barley	99.3	130.0	151.3	1.4	1.2	4.1	2.5
Other Cereals	115.6	141.2	164.9	1.0	1.0	5.0	3.4
Cotton	45.9	69.5	95.8	2.1	2.1	4.6	3.3
Vegetables	390.4	480.6	540.1	1.1	0.9	4.8	2.8
Sugar cane	969.5	2077.5	2517.1	3.9	2.8	3.6	1.8
Soybean	122.5	154.8	195.2	1.2	1.3	3.8	1.0
Other crops	1020.1	1322.3	1529.5	1.3	1.2	36.4	19.6

[1] The production projections are preliminary estimates from Oct. 1998 and are subject to continual revision.

slow in the 2015-2030 period compared to 1995-97 to 2015, reflecting the slowing population growth rate in the next century. Exceptions are expected for soybeans and cotton, which are likely to have faster growth rates in the later forecast period. Sugar cane and cotton exhibit the fastest growth rates (over 2 percent annually) during both projection periods.

With the exception of sugar cane in Latin America and other crops in East Asia, the regions with the largest current production of each of the crop categories all exhibit growth well below the expected global growth rate in both projection periods. Hence, part of the higher growth rates in many regions can be attributed to increased production from a relatively small 1995-97 base.

Some regional shifts in crop production are discernible from the FAO projections. For example, rapid growth (greater than 3 percent annually in one or both projection periods) is likely for maize in sub-Saharan Africa and the former Soviet Union; other cereals in sub-Saharan Africa; cotton in the former Soviet Union, South Asia and Oceania; rice in East Europe (from an extremely small base); barley in the former Soviet Union; sugar cane in Latin America and South Asia; and vegetables in South Asia. Conversely, several regions are expected to contract production for certain crops sometime during the next 30 years. Wheat, sugar cane, and maize production is expect to decline in Oceania; other cereals, vegetables and other crops in Western Europe; and other cereals in South Asia.

On a regional basis several trends are also apparent. The primarily developed countries of North America, West Europe, and Oceania are expected to show only modest growth (less than 2 percent annually), or in some cases declines, for nearly all crop categories (sugar cane in Oceania is an exception). East Asia also demonstrates modest production growth rates. Meanwhile, the former Soviet Union and sub-Saharan Africa are forecast to rebound from their relatively depressed production levels experienced during the 1990s. Rapid growth rates are also expected in other developing countries of the Near East, North Africa, Latin America, and South Asia.

Fertilizer Application Rates

Since the early 1990s, three organizations—IFA, IFDC, and FAO—have cooperated to produce statistics on fertilizer use by crop by country. The most recent edition was published in 1999 (FAO, 1999). A detailed description of the methodology used to estimate fertilizer application rates by crop and country

is given in Harris (1998). In general, the application rate data is based on expert opinion rather than on farmer surveys. Harris used the data to calculate aggregate fertilizer use by crop, nutrient, and country as well as show the positive association between yields and fertilizer application rates.

Harris noted that there are a number of weaknesses, limitations, and assumptions inherent in this database. Of particular concern to this study was the lack of IFDC/IFA/FAO fertilizer application data for certain countries. However, it was estimated that the database accounted for nearly 95 percent of global fertilizer use, since all the major agricultural countries are accounted for. In a number of countries, the IFDC/IFA/FAO database contained application rate data for a number of minor crops for which FAO did not project production. Again, this was considered a minor problem since these crops were not significant fertilizer users, see Tables 7 and 8.

Figures 4 and 5 indicate an estimate of the average annual amount of fertilizer (nutrient tons of N, P_2O_5, and K_2O) used on the major crops and by major country during the 1995-97 period. Clearly wheat, rice and maize are the major users of fertilizer and collectively account for over 50 percent of all global fertilizer use. Similarly, countries in East Asia, North America, South Asia, and Western Europe accounted for nearly 80 percent of all fertilizer use during 1995-97.

FIGURE 4
Fertilizer use by crop, 1995-97 (Source: FAO)

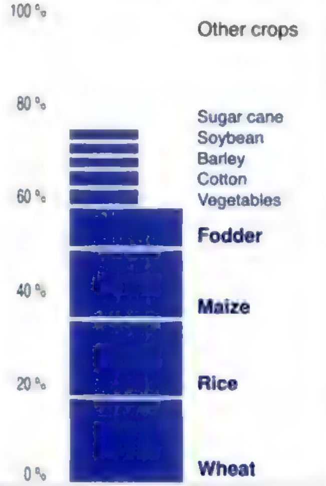
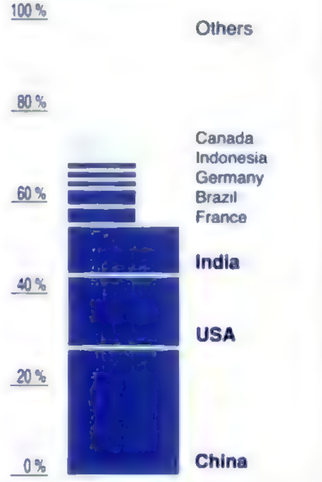


FIGURE 5
Fertilizer use by country, 1995-97 (Source: FAO)



The FAO country-level aggregate fertilizer use estimates for 1995 through 1997 were aligned with the application rates' share in the aggregate fertilizer use data from the IFDC/IFA/FAO publication. The fertilizer use share distribution was used to allocate the FAO three-year average (1995-97) annual fertilizer use figure across 34 FAO crop categories within each country. This assumes that the area of each crop and the application rates of fertilizer across the 34 FAO crop categories did not change significantly between the IFDC/IFA/FAO survey year and the 1995-97 period.

Methods for Deriving Fertilizer Use Estimates from Crop Production Projections

While numerous methodologies could be employed to derive estimates of mineral fertilizer use based on exogenously determined crop production projections, the paper uses three relatively straightforward techniques. The methods chosen for this analysis differ in the assumptions made about the relationship between yields and fertilizer application rates and how that relationship behaves over time by country and crop. In other words, each analytical method makes different assumptions about nutrient use efficiency over time.

Baseline scenario

Well-established physical relationships support the contention that increases in biomass require additional nutrient uptake. While the additional nutrients can be derived from both organic and mineral sources, the historical relationship between cereal production and mineral fertilizer consumption is well known (see Figures 2 and 3). The baseline scenario for fertilizer consumption in 2015 and 2030 is calculated from applying the anticipated crop production growth rate to the fertilizer quantity consumed in the 1995-97 base year (i.e., a 10 percent increase in maize production leads to a 10 percent increase in fertilizer use in maize production). Essentially, the output/input relationship between fertilizer use and crop production present in the 1995-97 base year is assumed to remain constant throughout to 2015 and 2030.

Algebraically, $FCROP_{t+1} = FCROP_t \,[\, 1 + (((A_{t+1})\,(Y_{t+1})) - ((A_t)\,(Y_t))) \,/\, ((A_t)\,(Y_t))]$ for each crop,

where t represents the current time period and:

FCROP	=	total fertilizer applied to crop
A	=	area planted
Y	=	yield

Increased nutrient use efficiency scenario

There is evidence that nutrient budgets[11] change over time and higher yields can be achieved through reduction of nutrient losses within cropping systems. That is, increases in food production can be obtained with a less than proportional increase in fertilizer nutrient use. Frink *et al.* (1998) showed this for maize in North America. Farmers achieve such an increased nutrient use efficiency through adoption of improved and more precise management practices[12]. While specific changes are difficult to identify, the trend cannot be ignored when long term fertilizer use projections are made[13].

In the absence of known crop production functions, future fertilizer application rates and nutrient use efficiencies were estimated by first quantifying the relationship between production and total fertilizer application rates that existed during 1995-97. Production was regressed on total fertilizer application rates (see IFDC/IFA/FAO data above) from FAO's database for all producing countries in each of the 34 FAO crop categories. That exercise provides an estimate of a global crop-specific fertilizer response coefficient. This response coefficient is then used in the calculation to compute future fertilizer application rates required to attain the projected increase in yields. Nutrient use efficiency improvements in each country and crop were assumed to be a function of the current yield/fertilizer use ratio, the fertilizer response coefficient, and the projected rate of change in the crop's yield (i.e., technological progress occurs among all crops and countries).

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[11] A nutrient budget is defined as the sum of nutrient inputs minus outputs (Goulding, 1998).

[12] Socolow (1998) suggests that such management technologies like precision agriculture offer abundant opportunities to substitute information for fertilizer.

[13] Agcaoili and Rosegrant (1995: page 70) note that "- fertilizer policy must shift from having a sole focus on increasing the level of use of fertilizer to also improving the efficiency of nutrient balance and the timing and placement of fertilizers".

Algebraically, for each crop and producer (country), the following relationship was constructed:

1. $F_{t+1} = F_t + (Y_{t+1} - Y_t)/(Y_t / F_t)$
2. $(Y_{t+1} / F_{t+1})_{ADJ} = (Y_{t+1} / F_{t+1}) + B((F_{t+1} - F_t)/ F_{t+1})$
3. $FTOT_{t+1} = (A_{t+1})(Y_{t+1})((Y_{t+1} / F_{t+1})_{AUG})^{-1}$
4. $F'_{t+1} = FTOT_{t+1} / A_{t+1}$

where t represents the current time period and:

F	=	unadjusted fertilizer application rate
Y	=	yield
A	=	area planted
$(Y/F)_{AUG}$	=	augmented fertilizer productivity
FTOT	=	total fertilizer use
B	=	global crop specific fertilizer response coefficient
F'	=	final fertilizer application rate

Equation 1 is the unadjusted estimate of the future fertilizer application rate based on the application rate in the preceding period plus the projected yield growth divided by the fertilizer productivity in the preceding period. Equation 2 is the future fertilizer productivity augmented by the fertilizer response coefficient times the estimated change in the fertilizer application rate. This relationship ensures that each country and crop will experience an increase in its fertilizer productivity from the previous period, given an increase in yields. In other words, all countries and crops are assumed to adopt technology that will lead to improved fertilizer productivity, as represented by the fertilizer response coefficient. The incremental productivity increase is also a function of the increase in yields projected by FAO. The inverse of the estimated fertilizer productivity times the projected crop production provides the total fertilizer consumption in 2015 and 2030 (equation 3). Equation 4 is the adjusted future application rate based on the improved fertilizer productivity.

An example using wheat in Turkey illustrates the above procedure. In the base period 1995-97, wheat received 63 kg fertilizer per ha and the yield was 1.9 t/ha. The fertilizer produc-tivity is 30 kg wheat per one kg fertilizer. The global wheat fertilizer response coefficient is 15.7 (Table 4). The projected yield for 2015 is exogenous and projected at 2.5 t/ha. The corresponding unadjusted fertilizer application rate in 2015 is estimated using the fertilizer application rate in the base period augmented by the yield difference between

the projected wheat yield for 2015 and the wheat yield in the base year over the fertilizer productivity in the base year (i.e. F_{t+1} = 63 + (2 465 - 1 893)/30 = 82 kg/ha; Table 5). The fertilizer productivity in 2015 is estimated by the projected yield over the projected fertilizer application rate augmented by the relative incremental fertilizer application rate adjusted by the fertilizer response coefficient (i.e. $(Y_{t+1} / F_{t+1})_{AUG}$ = 2 465/82 + 15.7*(82-63)/82 = 34). The preliminary fertilizer application rate in 2030 becomes the fertilizer application rate in 2015 augmented by the yield difference between the projected wheat yield for 2030 and the wheat yield in 2015 over the fertilizer productivity in 2015 (i.e. 82 + (2 727 – 2 465)/34 = 90 kg/ha). The fertilizer productivity in 2030 will be the fertilizer productivity of 2015 augmented by the relative incremental fertilizer application rate adjusted by the fertilizer response coefficient (i.e., 34+((90-82)* 15.7)/ 90 = 35). Hence, fertilizer productivity increases over time to attain projected yields in 2015 and 2030 (see Annex 1). The final fertilizer application rates, adjusted for the increased fertilizer productivity, are 73 kg/ha in 2015 and 77 kg/ha in 2030.

TABLE 4

Increased nutrient use efficiency scenario: computed nutrient use and crop response function parameters

	R^2	Coeff. x 1000	No. of observations
Banana	0.47	52.4	14
Barley	0.72	17.3	42
Cassava	0.87	256.6	5
Citrus	0.29	31.2	21
Coconut	0.58	119.7	5
Cocoa	0.63	2.0	6
Coffee	0.93	3.6	17
Cotton	0.97	8.8	26
Fibers	0.14	14.0	5
Fruit	0.81	39.5	33
Groundnut	0.98	13.1	11
Maize	0.99	25.1	63
Millet	1.00	24.9	3
Oil crops	0.89	23.1	12
Other cereals	0.83	21.8	33
Other roots	1.00	47.8	2
Oil palm	0.99	11.8	9
Plantain	0.80	83.9	4
Potato	0.59	53.7	59
Pulses	0.89	15.5	48
Rape	0.89	6.9	21
Rice	0.99	23.5	49
Rubber	0.91	10.4	5
Sesame	0.78	4.8	8
Sorghum	0.73	17.8	19
Soybean	0.61	27.0	18
Sweet potato	1.00	69.3	4
Sugar beet	0.87	139.1	30
Sugar cane	0.95	258.0	27
Sunflower	0.56	9.9	16
Teas	0.72	2.6	8
Tobacco	0.92	5.5	29
Vegetable	0.80	72.8	57
Wheat	0.93	15.7	58

TABLE 5
Turkey wheat example

	1995-97	2015	2030
Unadjusted application rate in kg fertilizer/ ha (F)	63	82	90
Yield kg/ ha (Y)	1 893	2 465	2 727
Fertilizer productivity: kg yield /kg fertilizer $(Y/F)_{ADJ}$	30	34	35
Area (000 ha) (A)	9 517	9 337	9 271
Fertilizer t (FTOT)	599 482	683 307	721 561
Final kg fertilizer/ha (F')	63	73	77

Fertilizer productivity, as measured by kg yield/kg fertilizer, shows considerable variation across countries, which likely reflects differing resource bases, production practices, management skills, and economic incentives. In Turkey, 1 kg fertilizer produces 30 kg of wheat and the yield is 1.9 t/ha. Similar application rates in west Europe result in yields of 6-7 t/ha. Fertilizer productivity positively relates to soil moisture availability. For example, irrigated wheat production in Zimbabwe and Saudi Arabia shows a ratio of 40 kg wheat per kg fertilizer nutrient and yields are 4.5 t/ha. Similar yields in Norway and the Czech Republic require fertilizer application twice as large. Furthermore, a high yield/fertilizer ratio may also indicate that fertilizer use is not widespread among farmers (i.e., wheat in Russia, Ethiopia and Algeria), or that high yields are obtained with other than fertilizer nutrient inputs (i.e., The Netherlands). Given this variability, however, the scope for higher levels of fertilizer productivity is substantial. The degree with which such productivity gains will be pursued depends, among other factors, on economic and public policy incentives.

Nitrogen use on cereals

An attempt was made to estimate the impacts on fertilizer use of the widespread adoption of similar production technology, including nutrient management practices, across the variety of crop production environments noted above. This exercise was restricted to nitrogen and the three major cereal crops. Nitrogen is often thought of as the "engine" of crop biomass production and is of major importance from both economic and environmental stand-points. The relationship between cereal yields and nitrogen application rates, which prevailed in the early 1990s, was first estimated. Selected major wheat, rice, and maize producing countries were included in the analysis (i.e., nitrogen application rates were regressed on yields since future yields were exogenously

TABLE 6

Linear regression of nitrogen application rate (kg/ha) on yields (t/ha) of wheat, rice and maize

Crop	Intercept (A)	Coefficient (B)	R^2	No. of observations[1]
Wheat	2.65	22.43	.80	40
Rice	- 29.39	27.73	.61	35
Maize	- 15.43	23.14	.76	42

[1] The number of observations for these crops was adjusted by elimination of outliers' country data to obtain an acceptable value for R^2 and consequently differs from the number of observations presented in Table 4.

TABLE 7

Estimates of total fertilizer use(million t) and average annual growth 1995-97 to 2015 and 2030 by crop and region: baseline scenario

	Fertilizer use			Growth	
Crop	1995-97	2015	2030	2015	2030
Barley	4.1	5.8	6.9	1.4	1.2
Sugar cane	3.6	7.7	8.2	3.9	2.8
Cotton	4.6	6.9	9.3	2.1	2.1
Maize	19.3	26.7	31.6	1.7	1.5
Other cereals	5.0	5.9	6.6	1.0	1.0
Rice	21.3	27.3	29.3	1.3	1.0
Soybean	3.8	5.0	6.0	1.2	1.3
Vegetables	4.8	5.6	6.2	1.0	0.9
Wheat	24.7	33.5	38.9	1.5	1.3
Others	36.4	42.3	47.0	1.3	1.2
sub-total	127.8	166.7	190.0	1.3	1.1
no yield data	0.2	0.2	0.3	1.3	1.1
no fertilizer data	6.0	7.8	8.9	1.3	1.1
Total	133.9	174.7	199.2	1.3	1.1
Region					
East Asia	45.5	55.9	62.0	1.0	0.9
East Europe	3.0	6.4	7.2	3.9	2.5
Former Soviet Union	3.9	5.1	5.7	1.3	1.1
Latin America	9.7	15.2	16.9	2.3	1.6
Near East & N. Africa	3.0	5.3	7.2	2.9	2.5
North America	22.6	27.9	31.7	1.1	1.0
Oceania	2.6	3.0	3.4	0.9	0.8
South Asia	18.1	27.1	33.5	2.0	1.8
Sub-Saharan Africa	1.4	2.3	3.0	2.7	2.3
West Europe	17.9	18.5	19.4	0.1	0.2
sub-total	127.8	166.7	190.0	1.3	1.1
no yield data	0.2	0.2	0.3	1.3	1.1
no fertilizer data	6.0	7.8	8.9	1.3	1.1
World	133.9	174.7	199.2	1.3	1.1

Note: quantities are in million nutrient tons of N, P_2O_5 and K_2O. Annual growth rates are compounded, not average, growth rates.

determined by FAO). Hence, cross-section data circa 1990-95 were used to predict nitrogen application rates in 2015 and 2030 (Table 6). This assumes that the major cereal producing countries will be adopting a similar production technology (and responding to similar economic factors) in future years. In essence, all countries were forced to exhibit a similar relationship between nutrient use efficiency and yield. Algebraically, for each country and crop the following was calculated:

$$N_{t+1} = A + B\,(Y_{t+1})$$

$$NTOT_{t+1} = (N_{t+1})\,(A_{t+1})$$

where: N = nitrogen application rate
A and B are regression coefficients
NTOT = total nitrogen use

Total Fertilizer Projection Scenarios

Baseline Scenario

By design, the growth in fertilizer consumption in the baseline scenario reflects the FAO yield and area projections to 2015 and 2030 for 34 major crop categories. The annual rates of growth in fertilizer use by commodity approximate the crop growth rates are reported in Table 3.

Under this scenario, fertilizer use is expected to grow from 133 million t per year to over 199 million t per year by 2030—a growth rate of about 1.1 percent annually (Table 7). Just as crop production growth was expected to decline in the 2015-2030 time period, primarily due to slowing population growth, so is fertilizer use. While wheat, rice and maize continue to dominate the demand for fertilizer into the next century, fertilizer use in maize production is expected to surpass that of rice by 2015. Not unexpectedly, the highest rates of growth occur in sugar cane and cotton production. East Asia is expected to remain the largest consumer of fertilizer with consumption running at twice the level of the next largest region—North America. However, by shortly after 2015, South Asia is likely to overtake North America. East Europe, the Near East and North Africa, and sub-Saharan Africa exhibit the highest fertilizer growth rates presumably reflecting the depressed crop production levels in the 1990s and the expected rebound in the next century. For a variety of reasons noted earlier, crop production, and hence fertilizer use, in West Europe is

expected to grow very slowly. In fact, the developed regions in general (North America, West Europe, and Oceania) are among the slowest growing fertilizer consumers of all the regions.

Increased nutrient use efficiency scenario

Imposing increased nutrient use efficiency on a global basis has the obvious effect of allowing crop production increases with the same or smaller quantities of fertilizer (Table 8). In this scenario, nutrient use efficiency was allowed to increase for all countries and crops from their 1995-97 base. Fertilizer growth rates are calculated to fall to about 0.7 percent annually over the next 35 years. Nevertheless, total nutrient use rises from 133 million t/year to 167 million t/year. Sugar cane and cotton production remain the largest growth markets, while other cereals and vegetables are expected to be stagnant or declining markets. The major cereals appear to be bidding land, and fertilizer, away from the minor cereal crops. Under this scenario, Latin America joins Eastern Europe and sub-Saharan Africa as the fastest growth markets through 2030. As above, the regions with primarily developed countries tend to be the fertilizer markets with the slowest growth.

Projections of nitrogen use on cereals

Because of its importance in cereal production as well as for environmental concerns, a third scenario examined nitrogen use (Table 9). A fairly robust relationship between application rates and yields for the three major cereal crops permitted the examination of nitrogen use given the assumption that the major cereal producing countries will adopt similar fertilizer use technology as yields increase in the future. This scenario did not result in significantly different estimates compared to the baseline scenario. The nitrogen fertilizer growth only increased from 1.5 percent annually to 1.57 between 1995-97 and 2015, and from 1.28 to 1.35 between 1995-97 and 2030. However, the final result is that nearly 2 million t/year of additional nitrogen are used on these three crops when all cereal producing countries adopt a similar production technology. This may not be too surprising given that this methodology can result in some countries increasing nitrogen use per kg of yield while others decrease use from their 1995-97 base. An extension of this methodology could be employed to examine the impact on nitrogen use when nitrogen use efficiency would be allowed to increase over time rather than remain constant as yields increase.

TABLE 8

Estimates of total fertilizer use (million t) and average annual growth 1995-97 to 2015 and 2030 by crop and region: increased nutrient efficiency scenario

	Fertilizer use			Growth	
Crop	1995-97	2015	2030	2015	2030
Barley	4.1	4.6	4.9	0.5	0.5
Sugar cane	3.6	5.9	6.9	2.5	1.9
Cotton	4.6	5.8	7.0	1.1	1.2
Maize	19.3	22.0	24.6	0.7	0.7
Other cereals	5.0	4.7	4.9	0.3	0.0
Rice	21.3	23.0	23.8	0.4	0.3
Soybean	3.8	4.1	4.7	0.3	0.6
Vegetables	4.8	4.2	4.1	0.7	0.5
Wheat	24.7	28.8	31.6	0.8	0.7
Others	36.4	41.1	45.5	0.6	0.6
sub-total	127.8	144.2	158.1	0.6	0.6
no yield data	0.2	0.2	0.2	0.6	0.6
no fertilizer data	6.0	6.7	7.4	0.6	0.6
Total	133.9	151.2	165.7	0.6	0.6
Region					
East Asia	45.5	49.2	52.5	0.4	0.4
East Europe	3.0	4.3	4.8	1.9	1.4
Former Soviet Union	3.9	4.6	5.1	0.8	0.8
Latin America	9.7	12.4	14.4	1.3	1.1
Near East & N. Africa	3.0	3.9	4.7	1.2	1.2
North America	22.6	24.4	26.4	0.4	0.4
Oceania	2.6	2.6	2.7	0.1	0.2
South Asia	18.1	22.2	25.5	1.0	1.0
Sub-Saharan Africa	1.4	1.8	2.2	1.5	1.4
West Europe	17.9	18.8	19.8	0.2	0.3
sub-total	127.8	144.2	158.1	0.6	0.6
no yield data	0.2	0.2	0.2	0.6	0.6
no fertilizer data	6.0	6.7	7.4	0.6	0.6
World	133.9	151.2	165.7	0.6	0.6

Note: quantities are in million nutrient tons of N, P_2O_5 and K_2O. Annual growth rates are compounded, not average, growth rates.

CAVEATS

The most recent demand and supply models suggest that there is little risk of a food crisis in the foreseeable future, although localized area of malnutrition, such as in sub-Saharan Africa, will persist (e.g. Rosegrant *et al.* 1998). However, these models are based on a number of assumptions that are either explicit or

TABLE 9

Estimates of nitrogen fertilizer use (million t) and average annual growth 1995-97 to 2015 and 2030 on cereals for three scenarios

	N Total (million t)			Growth	
Baseline Scenario					
Crop	1995-97	2015	2030	2015	2030
Wheat	16.3	22.2	26.3	1.6	1.4
Rice	15.0	19.3	21.0	1.3	1.0
Maize	12.1	16.8	20.5	1.7	1.5
3 crop subtotal	43.3	58.4	67.7	1.5	1.3
All crops	77.8	100.4	117.7	1.3	1.2
Improved Nutrient Efficiency Scenario					
Crop	1995-97	2015	2030	2015	2030
Wheat	16.3	19.1	21.0	0.8	0.7
Rice	15.0	16.2	16.7	0.4	0.3
Maize	12.1	13.9	15.6	0.7	0.7
3 crop subtotal	43.3	49.2	53.4	0.6	0.6
All crops	77.8	88.0	96.2	0.6	0.6
Nitrogen Scenario					
Crop	1995-97	2015	2030	2015	2030
Wheat	16.3	21.1	25.4	1.3	1.3
Rice	15.0	21.3	23.6	1.8	1.3
Maize	12.1	16.8	20.4	1.7	1.5
3 crop subtotal	43.3	59.2	69.4	1.6	1.4
All crops	77.8	106.3	124.5	1.6	1.4

implicit. For example the above scenario is critically dependent on: (i) slowing population growth; (ii) the assumption that per capita direct demand for cereal will remain constant while indirect demand, through livestock, will increase moderately; and (iii) yield growth continuing at historical rates. Other factors may impede this rather optimistic outlook such as: significant shifts in climate; further or accelerated mismanagement of irrigation projects; depletion of ocean fisheries; environmental degradation due to agricultural intensification (soil erosion, water and air pollution, deforestation, acidification, salinization, etc.); shifting pest pressures; biodiversity or genetic resource constraints; and adverse agricultural, trade, or environmental policies, including more severe regulatory constraints on biocides and plant nutrient sources (Johnson, 1998; Socolow, 1998).

Assumptions, limitations and extensions of the analysis

As every empirical study, this one has its limitations. Ideally, a crop-based model should have been developed for each of the 34 crop categories and for each country in which the crop is produced. Clearly, production factors, climate, resources, and other factors vary considerably by crop and country. However, such an endeavour would take years to complete and be fraught with data limitations. This study focused on three methodologies based on different assumptions about nutrient use efficiency. All three methods rely on FAO's preliminary estimates of 2015 and 2030 yields and areas for 34 crop categories by country as the primary driver of future fertilizer demand.

The baseline scenario presumes that an increase in the production of a given crop is accompanied by a proportional increase in fertilizer nutrient use. This scenario is overly simplistic because it ignores economic and other factors that will influence future fertilizer nutrient use. It also ignores future improvements in nutrient use efficiencies like those observed in North America and, thus, is likely to present an overestimate of future nutrient use in countries where such efficiencies are likely to occur. There are also numerous countries whose improvements in N-P_2O_5-K_2O balances are far from optimal, given the characteristics of the soils and the crops produced. In these countries, forecasts of nutrient use may overestimate actual future values as they move toward more balanced rates of application and hence, considerably higher nutrient use efficiencies.

The increased nutrient use efficiency scenario attempts to address some of the limitations of the base case scenario by allowing nutrient use to become more efficient over time as crop yields increase because high yields in the base period 1995-97 are associated with improved nutrient use efficiency. In this approach, regressions were run by crop across all countries using the crop response model: production = a + B* fertilizer. These regressions make implicit assumptions and are subject to some potential problems. Production was estimated to be a function of fertilizer use only as other factors typically hypothesized to impact crop yields were not included due to data limitations. The estimated relationships were assumed to be linear and simultaneity issues across crops were not incorporated. The cross-section regressions were run across different cropping technologies, resource bases, and economic systems and each observation was given an equal weight regardless of whether a country was a large or small producer of the particular crop. Estimates for several of

the 34 crop categories are based on a very limited number of observations available (Table 4), however, these crops are not significant fertilizer users. The model estimates used are also subject to the usual problems associated with cross-section analysis as well as the typical problems of estimating production functions.

The model estimated for the final scenario was a fertilizer requirements function: Nitrogen = A + B* (yield). The cross-section estimates used for this scenario make the same assumptions regarding the relationship between yields and fertilizer use (nitrogen, in this case) as the increased nutrient use scenario. Consequently, these estimates are subject to the same potential problems listed above.

Future research could focus on splitting the aggregate crop categories used in this study into more homogeneous groups. For example, two estimates could be developed for each crop by separating the data into developed and developing countries. The crop categories could also be separated into more than one group based on the level of crop yield attained. Another criterion for dividing the countries with respect to crop production would be to group them by similar production techniques as a proxy for distinct levels of technology.

A more detailed study of the fertilizer application data could also be undertaken in order to identify the countries where N : P_2O_5 : K_2O ratios for a particular crop are currently out of balance. While a case by case analysis may be necessary as there may be an economic reason why a country's N : P_2O_5 : K_2O ratio is currently out of balance, future fertilizer use for the crop(s) in these countries would be expected to move towards a more optimal balance over time. This improvement in nutrient-ratio balance could be incorporated into the model for the crops in these counties.

Conclusions and Implications

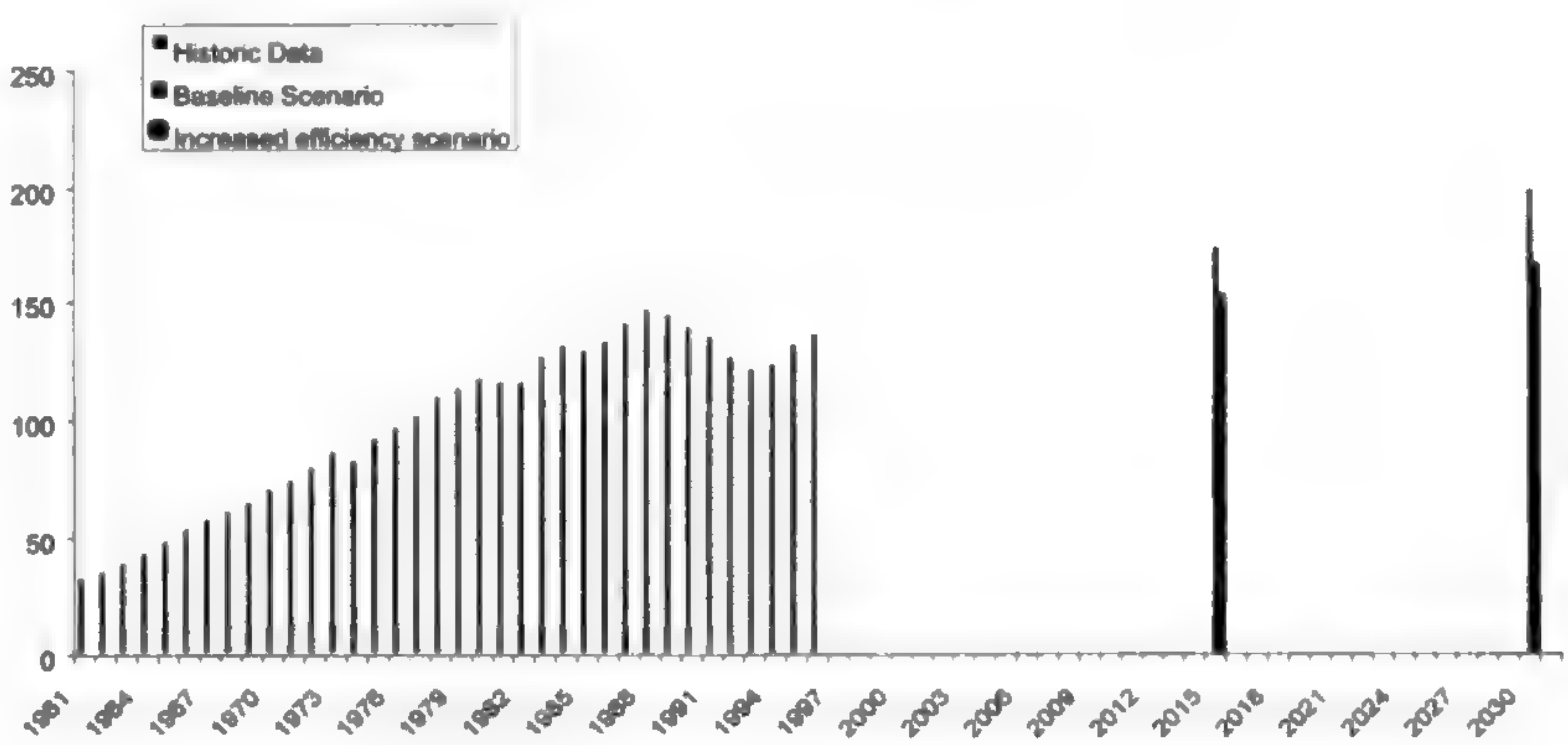
The most recent projective studies of global agricultural production into the 21st century suggest that a global food crisis is unlikely but that many countries and regions within countries will continue to suffer from chronic malnutrition. From a resource perspective, growing world population and per caput incomes will likely require more intensive agricultural crop production. Higher yields will in turn increase the demand for agricultural inputs, especially mineral

fertilizers. Furthermore, future agricultural cropping patterns will reflect shifts toward greater meat consumption. Greater opportunities for agricultural trade may also lead to regional shifts in world crop production. At the same time, there will likely be economic and environmental incentives to improve the efficiency of fertilizer use over current levels in all countries, but especially in the developed countries.

This analysis attempted to place bounds on the amount of fertilizers needed to support FAO's yield and area projections to 2015 and 2030. It is expected that total fertilizer use will increase from about 133 million t per year in 1995-97 to between 167 and 199 million t per year by 2030. These estimates represent annual growth rates of between 0.7 to 1.3 percent depending on the assumptions about nutrient efficiency over the next 35 years. These rates of growth are similar to those estimated in other studies, which indicate a slowing in the growth of fertilizer use. Satisfying the growth in demand for food in the 21st century will clearly require further increases in fertilizers but at lower growth rates compared to the last 40 years.

The maturing of fertilizer markets during the 1980s in North America and Western Europe, two of the major fertilizer consuming regions of the world,

FIGURE 6
World fertilizer nutrient consumption, million t



account for much of the projected slowed growth rate in the future compared to the past. Furthermore, the rapid growth rate in the 1960-90 period can be partly attributable to the very small fertilizer consumption base in developing (and in some cases developed) countries during the early part of that period.

Wheat, rice and maize will continue to dominate fertilizer markets with the expectation that fertilizer use on maize will exceed rice by 2030—a consequence of greater demand for meat in developing countries. East Asia will likely continue to dwarf fertilizer consumption in its nearest competitors—North America and South Asia. Growth in fertilizer use in the developed countries, especially Western Europe, is expected to lag significantly behind other regions of the world.

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Annex 1

Projected fertilizer productivity, wheat yield > 3 t/ha

3 < yield < 4 t / ha			4 < yield < 7 t / ha			yield > 7 t / ha		
	1995-97	2030		1995-97	2030		1995-97	2030
Italy	3.3	4.7	Mexico	4.1	5.9	Denmark	7.0	9.9
Japan	3.3	3.6	Saudi Arabia	4.4	4.7	Germany	7.0	9.9
Chile	3.5	3.9	Zimbabwe	4.5	6.4	Belgium	7.7	11.0
Poland	3.5	5.5	Czech Rep.	4.6	5.8	U.K.	7.7	11.0
Croatia	3.8	4.8	Austria	5.1	7.2	Ireland	8.4	11.8
Hungary	3.8	6.0	Egypt	5.4	8.5	The Netherlands	8.6	12.2
Finland	3.9	5.5	Sweden	5.8	8.2			
			France	6.8	9.6			

This study on future fertilizer requirements in agriculture projects total fertilizer use to increase from the current levels of about 133 million tonnes a year to between 167 million and 199 million tonnes a year in 2030. The forecast growth rates are slower than those of the past 40 years, which averaged 5.5 percent annually. Taking account of the "likely future path of global agricultural production and resource use" – including environmental incentives to improve the efficiency of fertilizer use in developed countries – the study projects growth rates of between 0.7 and 1.3 percent, depending on assumptions about nutrient efficiency over the next 35 years.

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